CHAPTER 20
Control of Icing on Hydraulic Structures

20-1. Introduction

a. As described in Chapter 14, the ice-related problems at hydraulic structures are severe during winter months. Exposed mechanically operated systems, such as spillway gates, may be frozen-in and become inoperable. The weight of ice on structures that need to be moved (e.g., dam gates) may become excessive so that the lift system becomes overloaded. Ice loads can also cause structural damage. Icing on recess walls or gates of navigation locks prevents full use of the lock width. Ice buildup on dam pier walls can obstruct the movement of the components of the dam gate. Ice accumulation on water intakes, either municipal or hydropower, reduces the capacity to pass water through the intake, leading to water shortages or reduced power production. If the intakes become completely blocked, they may sustain structural damage. Ice buildup on walkways poise a safety hazard to personnel. All of these ice problems involve ice formation on or adhesion to critical surfaces on hydraulic structures.

b. Through careful consideration of the wintertime operation of a hydraulic structure, many icing problems can be eliminated during the design phase. For example, gate machinery and strut arm pivot points often can be relocated during the design phase to place them out of the water or splash zones, so that they do not become wetted and then covered with ice. Furthermore, icing of dam gates is often a result of small quantities of water leaking by seals. This is not an issue during warm conditions, but this small, steady flow of water can lead to sizeable ice accumulations in the course of just a few cold days (see Figure 20-1) rendering equipment inoperable until the ice is removed. Careful attention to seal design can help avoid these problems.

c. Unfortunately, not all of the icing problems can be designed out of project, and some form of icing control needs to be employed to maintain winter operations. This chapter addresses several approaches to solving problems resulting from ice adhering to components on hydraulic structures. These include heating surfaces to prevent ice formation or reduce ice accumulation, improved sealing of gates, application of surface treatments to reduce the force required to remove ice from the surface, and mechanical methods for removing ice. Guidance for the design and installation of these systems is provided.

20-2. Heating of Components

a. Introduction. The most reliable method for controlling icing is to keep the temperature of the surface to be protected above 0°C (32°F). This method is most effectively integrated into the hydraulic structures during the original design and construction of the project. Yet, there have been many successful retrofits of heating systems into existing structures.

(1) Heat has been used for years at hydraulic structures to control icing. Typical methods include steam lances, heat tracing embedded in concrete walls, and mineral insulated (MI) heaters installed under steel side-seal rub plates. Though these have proven effective, they all have demonstrated limitations. Steam lances pose the same problems as pike poles and other manual methods in that they are very labor intensive and slow, and they frequently place personnel in

hazardous locations on the lock or dam. Placing heat where it is needed using heat tracing is desirable, yet the practice of embedding heat tracing in concrete typically provides only a short-term benefit, as the heaters burn out after relatively short service and cannot easily be replaced. Placing side-seal rub plate heaters that have replaceable electric elements on dam gates was beneficial, but the limited area that was heated did not entirely prevent the gates from freezing shut.

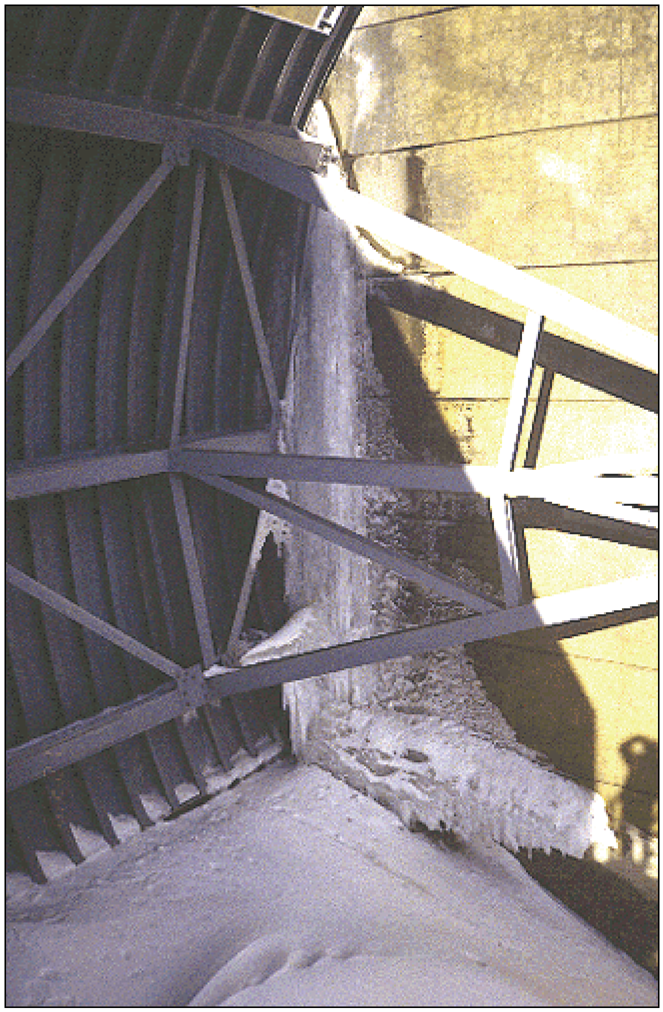


Figure 20-1. Column of ice formed on the downstream side of a tainter gate from water leaking past the side seal. The ice forms a bridge between the gate and pier. Such accumulations prevent movement of the gate. To restore normal gate operations, the ice needs to be removed by melting, chipping, or cutting. Photo of Gavens Point Dam, Yankton, SD.

(2) For example, Figure 20-1 shows ice accumulated on the downstream side of a tainter gate at Gavins Point in Yankton, SD. These gates had heaters to prevent the side seal from freezing to the steel rub plate. However, because of the low heat conduction of the surrounding concrete, the heat from the 10-kW elements remained confined to the vicinity of the rub plate. Water leaking by the side seal froze and then formed an ice bridge between the gate and pier wall, freezing the gate solidly in place. To prevent the gate from freezing, the heater needs to extend over an area large enough to melt most, if not all, of the ice off of the wall and gate. The enclosure for the heater must have high conductivity (e.g., that of aluminum or steel) so that the heat is distributed uniformly over the area. Furthermore, provision for easily replacing the heater elements when they fail must be designed into the enclosure. Heaters can be turned on in the fall and thermostatically controlled throughout the winter.

(3) This paragraph provides guidance for sizing of heater systems and basic design considerations for installing heaters in concrete walls, gates, sills, intakes and other critical components.

b. Heater Sizing. Most of the surfaces that need to be protected from ice can be classified under three general categories: walls, gates, and intakes. What follows are basic design calculations for computing the heat loss associated with each of these three categories, which is then used to determine the minimum power required to protect the component from ice. The formulas presented provide an estimate of the heat loss for many situations, but are not applicable to all situations. For complicated geometries, two- or three-dimensional heat transfer calculations may be required and computational methods, such as finite element codes, can be employed to determine the heat loss from the surface to be protected.

(1) *Walls*. Typically it is the concrete walls of lock or dam piers that require deicing. Ice accumulation on lock walls (Figure 14-4) are a result of fluctuating water level, resulting in a progressive thickening of the ice with each successive filling and emptying of the lock chamber. On dam piers, often leakage of water by the side seals of the gate result in long columns of ice forming a bridge between the gate and pier on the downstream side of the gate (Figure 20-1). What follows are design calculations for proper sizing of surface heater panels that can keep ice from forming on such concrete walls.

(*a*) The geometry of a typical heater panel installation is shown in Figure 20-2. The heat loss from a heating panel mounted on the surface of a wall is the combination of the convective heat transfer to the air and the conductive heat transfer into the wall. The heat panel source has to provide enough power to maintain the temperature of the surface above freezing despite these heat losses. The power requirements for the heating panel are simply the sum of these two losses

$$q_{\text{total}} = q_{\text{air}} + q_{\text{wall}} \qquad (20\text{-}1)$$

where

q_{total} = required heating power of the panel
q_{air} = heat lost to the air
q_{wall} = heat lost to the wall.

The heat loss to the air is computed from

$$q_{\text{air}}(\text{W m}^{-2}) = h(T_{\text{surface}} - T_{\text{air}}) = h\Delta T = h27 \tag{20-2}$$

where

T_{air} = ambient air temperature
T_{surface} = surface temperature of the wall or heater panel surface temperature
h = average convective heat transfer coefficient.

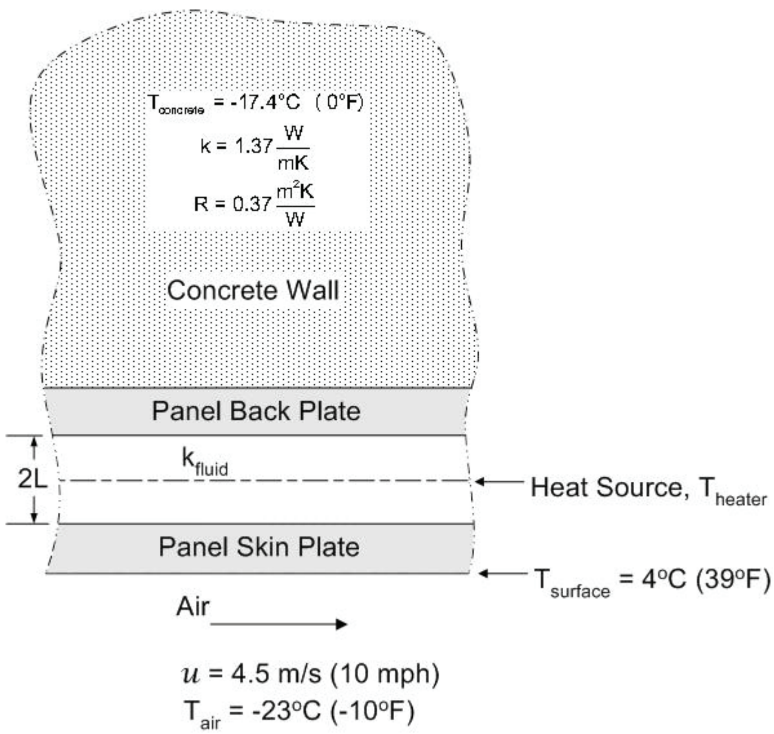


Figure 20-2. Geometry of a typical wall heater panel. The space between the skin and back plates of the heater is filled with a fluid with a thermal conductivity of k_{fluid}. This fluid is commonly air, but can also be glycol.

(*b*) For design, the air temperature is taken to be –23°C (–10°F). For extreme conditions a lower air temperature may need to be used, yet within the continental United States this seems adequate. The surface temperature is 4°C (39°F), yielding ΔT = 27°C. Ideally, it would be better to be able to maintain the surface temperature closer to the freezing point (e.g., 1°C); however, owing to uneven heating of the surface, there are quite often cold and hot spots on the heater panel. Experience has shown that designing wall heaters using T_{surface} = 4°C keeps even the cold spots on the heater panel above freezing.

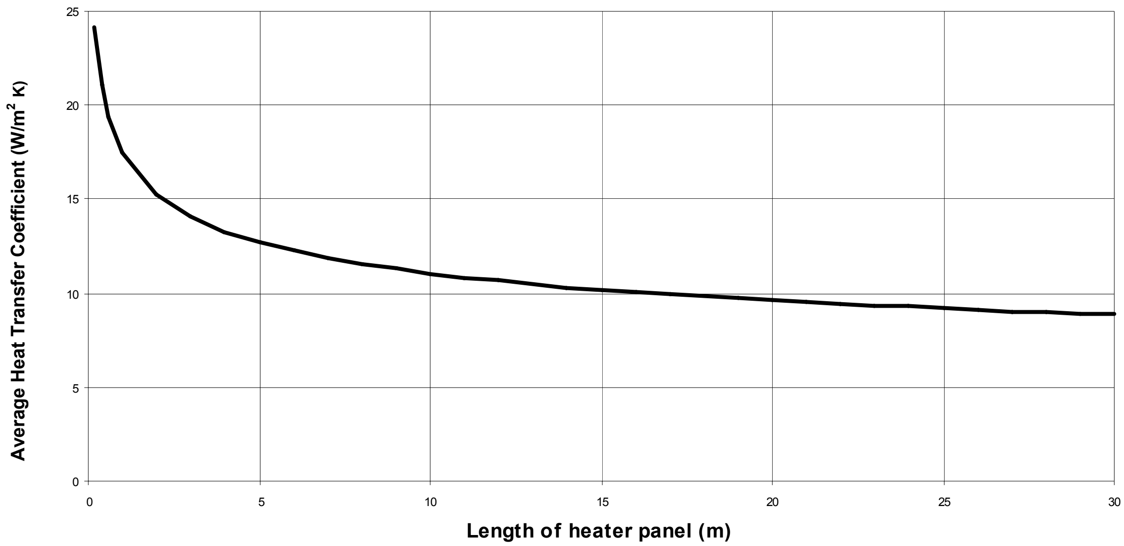


Figure 20-3. Estimate of average heat transfer coefficient in air from a flat surface as a function of the length (long-axis) of the heater panel based on the Chilton-Colburn Analogy. This is based on wintertime air properties where the air temperature is taken to be –23°C (–10°F), which gives a Prandtl Number of 0.72, a kinematic viscosity of 1.14×10^{-5} m^2/s, and thermal conductivity of 0.022 W/m K. For this chart an average wind speed of 4.5 m/s (10 mph) is used.

(*c*) Figure 20-3 gives approximate values of the average heat transfer coefficient, based on the design air temperature and a design wind speed of 4.5 m/s (10 mph), needed for computing the heat loss to the air using equation 20-2. In extreme climates, it may be desirable to use a higher value for the design wind speed, in which case

$$h(\mathrm{W\ m^{-2}K^{-1}}) = 0.0296\frac{\left(\dfrac{ux}{v_{\mathrm{air}}}\right)^{4/5}\mathrm{Pr}^{1/3}\,k_{\mathrm{air}}}{x} = \frac{5.26u^{4/5}}{x^{1/5}} \qquad (20\text{-}3)$$

where

u = wind speed
x = length of heater panel (long axis)
v_{air} = kinematic viscosity of air (1.14×10^{-5} m^2/s)
Pr = Prandtl number for air (0.72)
k_{air} = thermal conductivity of air (0.022 W/m K)

Equation 20-3 is based on the Chilton-Colburn Analogy (which is a reasonable approximation of the average heat transfer coefficient over a flat plate) and was used to compute the curve given in Figure 20-3.

(*d*) To estimate the heat loss into the wall

$$q_{\text{wall}}(\text{W m}^{-2}) = \frac{T_{\text{heater}} - T_{\text{wall}}}{R_{\text{wall}}} = \frac{T_{\text{heater}} + 17.4}{0.37 + L / k_{\text{fluid}}} \tag{20-4}$$

where

T_{wall} = the temperature of the concrete in the wall, 17.4°C (0°F)
R_{wall} = thermal resistance of the wall
L = half the thickness of the fluid in the panel (Figure 20-2)
k_{fluid} = thermal conductivity of fluid in the heater panel.

To use Equation 20-4, an estimate of the temperature of the heater needs to be obtained. Typically, the skin plate is made out of metal (aluminum or steel), so the thermal conductivity of these are much higher than the fluid and T_{heater} is approximately

$$T_{\text{heater}}(\text{C}) = T_{\text{air}} + \left(T_{\text{surface}} - T_{\text{air}}\right)\left(1 + \frac{hL}{k_{\text{fluid}}}\right) = -23 + 27\left(1 + \frac{hL}{k_{\text{fluid}}}\right) \tag{20-4}$$

where h is determined from Figure 20-3 or Equation 20-3. Values for the thermal conductivity of the fluid in the panel are given in Table 20-1.

Table 20-1
Values for the thermal conductivity of typical fluids in the heater panel

Fluid	**Thermal Conductivity, k_{fluid} (W/m K)**
Air	0.026
Gycol	0.25

(2) *Gates*. Another chronic problem arises when ice forms on a gate. This can freeze the gate in place so that it cannot be moved (see Figure 20-1) or a large amount of ice accumulates on the gate and increases the weight of the gate so that the lift machinery is overloaded. Also, ice collars can form on lock gates preventing the gate from fully recessing into the wall, thereby restricting barge width. The heat transfer for many of the situations where ice forms on a gate can be classified in two cases:

- Water on one side air on the other.
- Similar fluid on both sides of the gate.

In both of these cases only the situation where the gate is closed (the water velocity is less than 0.6 m/s [2ft/s]) is considered. The reason for this is the heat losses associated with water flowing over a heated surface (velocity greater than 0.6 m/s) are so large that operational costs associated with keeping the surface ice-free are prohibitive. Thus, the standard operating procedures for the heaters and gates should take into account that heaters will be ineffective when the gates are open. This will be discussed further in Paragraph 20-2*b*. In the following two subparagraphs, design calculations for sizing the heaters for closed gates are provided.

(*a*) *Heat Loss from a Closed Gate, Water on One Side, Air on the Other*. Figure 20-4 shows the basic geometry of a heater panel mounted on a closed gate. The total heat loss is the sum of the heat lost to the water and air

$$q_{\text{total}} = q_{\text{water}} + q_{\text{air}} \tag{20-6}$$

where

q_{total} = required heating power of the panel
q_{water} = heat lost to the water
q_{air} = heat lost to the air.

Using the design conditions of u = 4.5 m/s (10 mph) and an air temperature of –23°C (–10°F), the heat loss to the air can be computed using equation 20-2, where the heat transfer coefficient is determined from Figure 20-3. For more extreme conditions, the heat transfer coefficient can be determined from Equation 20-3. The heat loss to the water is computed from

$$q_{\text{water}} = \frac{T_{\text{heater}} - T_{\text{water}}}{\dfrac{1}{h_{\text{water}}} + \dfrac{L}{k_{\text{fluid}}}} \tag{20-7}$$

where

h_{water} = heat transfer coefficient for water interface
T_{heater} = temperature of heater plate
T_{water} = water temperature
L = half the thickness of the fluid in the panel
k_{fluid} = thermal conductivity of fluid in the panel.

The water temperature is 0°C (32°F); the heater temperature is determined from Equation 20-5 and k_{fluid} is given in Table 20-1. The heat transfer coefficient for the water is determined from

$$h_{\text{water}}(\text{W m}^{-2}\text{K}^{-1}) = 0.0296 \frac{\left(\dfrac{ux}{v_{\text{water}}}\right)^{4/5} \text{Pr}^{1/3} k_{\text{water}}}{x} = \frac{1060}{x^{1/5}} \tag{20-8}$$

where

u = water velocity (0.6 m/s or less)
x = length of heater panel (long axis)
v_{water} = kinematic viscosity of water (1.76×10^{-6} m^2/s)

Pr = Prandtl number for water (13)
k_{water} = thermal conductivity of water (0.569 W/m K).

Equation 20-8 is based on the Chilton-Colburn Analogy and provides a reasonable estimate of the average heat loss to the water.

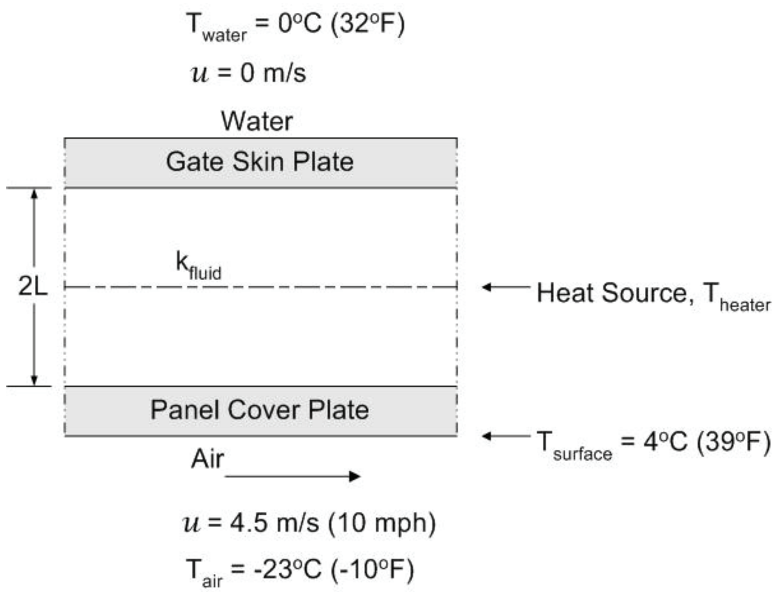


Figure 20-4. Geometry of a typical gate heater panel. The space between the panel cover and gate skin plates of the heater is filled with a fluid with a thermal conductivity of k_{fluid}. This fluid is commonly air, but can also be glycol.

(*b*) *Heat Loss from a Submerged Gate, Fluid the Same on Both Sides of the Gate*. In some instances, ice will accumulate on a gate that is fully submerged in water (water is on both sides of the gate). This is usually the result of frazil ice being present in a river that becomes deposited on the gate and freezes the gate in place. Ice can also accumulate on a gate that, for part of the time, is partially submerged, and, for part of the time, is in air. An excellent example of this is a lock miter gate, where the ice accumulates during cyclic filling and draining of the lock chamber. In this situation the heaters may be used to shed the ice off of the gate while the chamber is empty and the gate is fully submerged in air. The heat transfer calculations that follow provide a means to determine the heat loss for these cases. A typical heater configuration for this situation is shown in Figure 20-5. The heat loss to the surrounding fluid can be computed from

$$q_{\text{total}} = 2q_{\text{fluid}} = 2h_{\text{fluid}}(T_{\text{surface}} - T_{\text{fluid}}) \tag{20-9}$$

where

q_{fluid} = heat loss to surrounding fluid

$T_{surface}$ = surface temperature of skin plate, 4°C (39°F)
T_{fluid} = temperature of the surrounding fluid (water or air)
h_{fluid} = heat transfer coefficient for the fluid.

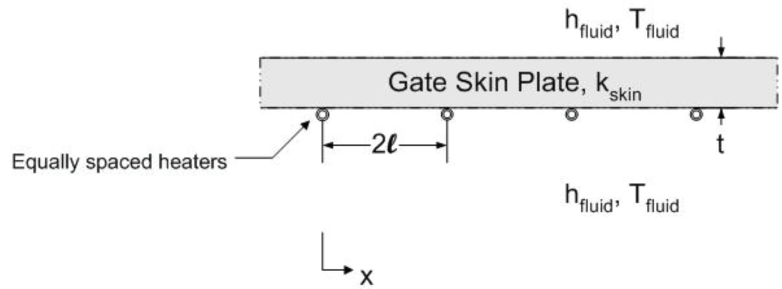


Figure 20-5. Heater configuration for a gate fully submerged in a fluid. The heaters are mounted to the back of the skin plate with a spacing of 2*l*. The heaters are treated as point sources.

Again the design temperature for the skin plate is 4 C°(39°F). The temperature of the fluid depends on the fluid type (water or air). Table 20-2 provides design temperatures for the fluid. For a panel operating in air, the heat transfer coefficient can be determined from Figure 20-3 or Equation 20-3; in water, the heat transfer coefficient can be determined from a modified form of Equation 20-8

$$h_{water}(\text{W m}^{-2}\text{K}^{-1}) = 0.0296\frac{\left(\dfrac{ux}{\nu_{water}}\right)^{4/5}\text{Pr}^{1/3}\,k_{water}}{x} = \frac{1590u^{4/5}}{x^{1/5}} \qquad (20\text{-}10)$$

where

u = water velocity (> 0.1 m/s or 0.3 ft/s)
x = length of heater panel (long axis)
ν_{water} = kinematic viscosity of water (1.76×10^{-6} m^2/s)
Pr = Prandtl number for water (13)
k_{water} = thermal conductivity of water (0.569 W/m K).

Table 19-2
Design values for the temperature and velocity for water and air

Fluid type	Temperature, °C (°F)	Velocity, m/s (mph)
Water	0 (32)	Site specific
Air	–23 (–10)	4.5 (10)

Equation 20-10 is based on the Chilton-Colburn Analogy. To use Equation 20-10, an estimate of the water velocity in the proximity of the gate is required. For velocities below 0.1 m/s (0.3 ft/s), a conservative estimate of h_{water} is obtained if u = 0.1 m/s is used. Generally, the water velocity is not zero in the vicinity of a gate because of turbulence from flow through adjacent gates or intakes, and wave action. An estimate of the water velocity near the closed gate can be made based on the average water velocity in the river on which the project resides. This can be determined from

$$u = \frac{Q_{\text{winter}}}{A} \qquad (20\text{-}11)$$

where Q_{winter} = winter time discharge on the river, and A = cross-sectional area of the river at the project. Once an estimate of the heat loss at the gate is determined, the spacing and number of the heater elements can also be determined by treating the skin plate as a fin with point sources of heat spaced at regular intervals across the plate. The spacing of the heat sources needs to be close enough so that the dip in temperature between the sources stays above 0.5°C. The heater spacing, $2l$, and size of individual heaters are both a function of the number of heaters on the surface of the skin plate, that is

$$Q = \frac{q_{\text{total}} WL}{N} \qquad (20\text{-}12)$$

Q = size of each heater (W)
q_{total} = total heat loss from gate (W/m^2)
W = width of the heater panel (m)
L = length of the heater elements (or height of the heater panel) (m)
N = number of heaters in the panel.

The heater spacing is $2l$, as indicated in Figure 20-5, and is determined from

$$l = \frac{W}{2(N+2)} \qquad (20\text{-}13)$$

In Equation 20-12, both Q and N are not known and need to be iteratively solved for. To do this a constraint on the spacing has to be applied to assure the minimum temperature on the panel surface is at or above 0.5°C. This constraint is applied by understanding that the basic heat transfer equation for this geometry is a fin of length, l, with the tip of the fin having an adiabatic boundary condition and the heat source is located at the root of the fin (i.e., the fin has periodic symmetry about the tip and root). Applying the analytical solution for a fin of this geometry, one can use the following iterative procedure to determine Q, N, and l:

- Step 1. $m = \sqrt{\dfrac{h_{\text{fluid}} P}{k_{\text{skin}} A}}$ (20-14)

where

h_{fluid} = convective heat transfer coefficient

k_{skin} = thermal conductivity of the skin plate (or fin)
P = perimeter of the fin section = $2(L+t)$
A = area of the fin section = Lt
t = thickness of skin plate.

- Step 2. Make an initial guess for l. A good starting point is around 0.2 m (0.7 ft).

- Step 3. $N = \dfrac{W}{2l} - 2$ (20-15)

- Step 4. Solve for Q using Equation 20-12

- Step 5. $T_b - T_{fluid} = \dfrac{Q}{\sqrt{h_{fluid} P k_{skin} A}\ \tanh ml}$ (20-16)

where T_{fluid} = fluid temperature, and T_b = temperature at the root of the fin.

- Step 6. $T(l) = T_{fluid} + (T_b - T_{fluid}) \dfrac{1}{\cosh ml}$ (20-17)

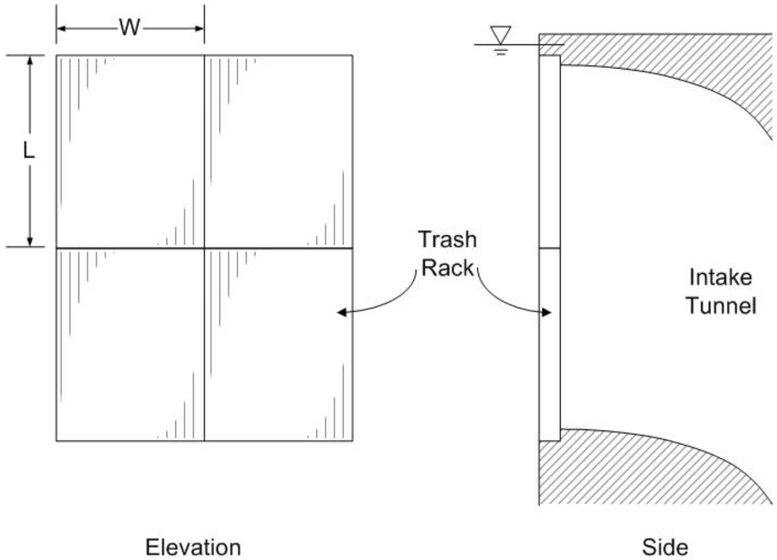
where $T(l)$ = temperature on the skin plate at a distance l from the heater.

- Step 7. Check to see if $T(l)$ =0.5°C. If it is less than 0.5°C, l needs to be reduced, if it is greater than 0.5°C, l needs to be increased.

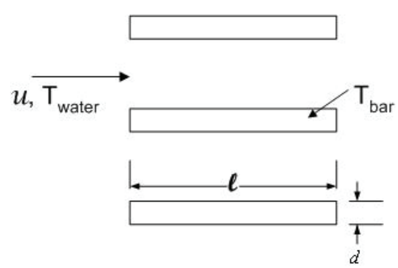
- Step 8. Continue steps 2 through 7 until the condition at 7 is satisfied.

Following this procedure does not provide a unique combination of Q, N, and l. However, the size of the heater, Q, is limited by what is available in the market, so choice of l must be controlled to give a Q that can be supplied by available heating equipment. As a starting point heaters that provide 1 kW/m (0.3 kW/ft) or more are commonly available. However, consultation with heater vendors is advised to get a more accurate determination of available heater capacity.

(3) *Intake Trash Racks*. Frequently, frazil ice accumulates on intake trash racks for municipal water or power tunnel intakes. This can reduce the flow through or completely block the intake. Figure 20-6 shows the basic geometry of a typical trash rack configuration on an intake.



a. An intake with trash racks covering the opening.



b. Detail of the fluid flow and heat transfer conditions around the individual bars on the trash rack.

Figure 20-6. Typical trash rack configurations.

(*a*) Logan (1974) provides an analysis of the heat needed to keep the trash rack bars free of frazil ice accumulations and is summarized here. The heat loss, Q, from the bars is computed from

$$Q = hPL(T_{\text{bar}} - T_{\text{water}}) \tag{20-18}$$

where

L	=	length of the trash rack bar
P	=	perimeter of the cross-section of the bar, $2(d + l)$
l	=	width of trash rack bar
T_{bar}	=	temperature of the bar (0.5°C)
T_{water}	=	water temperature (0°C).

(*b*) The required heat transfer coefficient, h, is determined from

$$h(Wm^{-2}K^{-1}) = 0.6\frac{k_{\mathrm{f}}}{d}\sqrt{\frac{ud}{\nu}}\,\mathrm{Pr}^{0.31} = 551\sqrt{\frac{u}{d}} \qquad (20\text{-}19)$$

where

k_{f} = thermal conductivity of water at the freezing point (0.55 W m^{-1} K^{-1})
d = thickness of the trash rack bar (m)
Pr = Prandtl Number (13)
u = water velocity (m/s)
ν = kinematic viscosity of the water (1.76×10^{-6} m^2/s).

(*c*) The water velocity passing through the trash racks is on average

$$u = \frac{Q_{\mathrm{intake}}}{ML(W - dN)} \qquad (20\text{-}20)$$

where

Q_{intake} = volumetric flow rate through the entire intake
M = number of trash racks covering the intake
L = height of an individual intake trash rack
W = width of an individual trash rack
N = number of bars in an individual trash rack.

(*d*) Using Equations 20-17 through 20-19 allows the heat required to keep ice off of a single trash rack bar to be determined. The heat required for the entire intake is

$$Q_{total} = NMQ \qquad (20\text{-}21)$$

(4) *General Remarks.* Table 20-3 lists typical power requirements, based on data obtained from heaters that are in service. This provides a rough guide for the power needed for the various applications described above. Also given in Table 20-3 is an estimate of the energy consumed for each ice shedding cycle, based on it taking approximately 15 minutes from the time the heaters are turned on until the ice releases from the surface. This is important as it gives an indication of the operational cost (i.e., the cost of fuel or electricity needed to operate the heater panels).

Table 20-3
Power and energy requirements for complete removal of ice using various heater types (after Haehnel et al. 2002)

Heater type	Power density (kW/m²)	Energy density (kJ/m²)	Approximate response time (min)
Wall heater panels on riverine structures (in air)[1]	0.6–0.7	540–630	15
Heater panels on riverine structures (immersed)[2]	4.5	3900	15
Trash rack heaters (immersed)[3]	2–6.7	—	Used in continuous anti-icing mode

[1]Haynes et al. (1997), Bockerman and Wagner (1998).
[2]Haehnel and Clark (1998).
[3]Billfalk (1987), Reid (1928), Samsioe (1924), Ruths (1924), Logan (1974), Daly et al. (1992).

c. Heater Design.

(1) *General Design Guidance.* It is also important to make provision for the heaters to be serviceable. The use of embedded electrical heaters that cannot be removed for replacement without major rehabilitation is *not recommended.* Almost every navigation project that has installed embedded electrical heaters has some heaters that have failed and cannot be replaced. Some approaches to providing replaceable heaters are described in the following subparagraphs.

(*a*) In some cases the heaters can only be replaced by divers. When this is true, the heaters need to be easily accessible and require that little dexterity is necessary in doing the replacement. Consideration should also be given to having the same size fasteners for cover plates and heater clamps so the divers need only use one size wrench to replace all of the heaters. Furthermore, the heater enclosures should be designed to provide easy access to the heaters once the covers are removed.

(*b*) Another consideration when designing for replaceable electrical heater elements is the routing of the power feed cables and location of junction boxes. Careful consideration needs to be given to this the make sure that the junction is above the water line and that feeding the cold leads in and out of the conduits is easily done.

(*c*) Another consideration is the type of material used in the heater assemblies, i.e., aluminum vs. steel. The conductivity of aluminum is significantly higher than steel and will allow the individual heater elements to be spaced further apart and still provide uniform heat on the surface to be protected. For example, in one application, by using an aluminum cover plate, the heaters could be spaced 15 inches apart, while a steel plate of the same thickness required a heater spacing of 2.5 inches. Yet, thicker aluminum plates are required to provide the same structural integrity as steel plating. Thus, careful consideration of the type of material used and the environment it is being subject to is required to balance these design considerations.

(*d*) Paramount to designing an effective icing control system is identifying where the ice may form and how it will affect operations. This allows identification of where heaters are needed and the size of the area that needs to be heated. In the case of existing projects, this is generally easy to determine by inspection. However, for submerged components (e.g., tainter valves), it is more difficult to determine where heaters will provide the greatest benefit as the locations where the ice forms cannot be viewed during normal operations. Furthermore, in the case of new projects, it is often difficult to assess in advance where ice will form and how it will affect operations. Yet, from experience several chronic problem areas have been identified and are as follows:

- Tainter gate side-seal or rub plate and pier or lock walls.
- Trunion arm.
- Gate skin plate.
- Intakes.

The following subparagraphs address basic design considerations for protecting these components with heaters.

(2) *Rub Plate and Wall Heaters.* It is preferred that rub plate heaters be imbedded in the walls so that they are flush with the surrounding concrete. If it is necessary for these panels to be surface mounted (i.e., retrofitted to a project), special consideration needs to be given to avoiding the forces of debris, water, ice, barges, etc., that can tear the panel off the wall.

(*a*) For tainter gates that have water on the upstream side and air on the downstream side, ice columns, as depicted in Figure 20-1, frequently form because of the water leaking past the side seal. The heater needs to be wide enough to melt the ice adhering to the pier wall. In the case of retrofits, the required width of the heater panel can be estimated from photographs such as Figure 20-1 or from actual measurements made on the structure. For new construction, it is difficult to estimate in advance how wide the ice column will be. Experience has shown that generally the heater panel needs to be at least 1.2 m (4 ft) wide and, for new construction, it is recommended that the heater panels be at least this wide, i.e., the heater should extend 1.2 m downstream of the side seal and follow the arc of the gate from the water level to the bottom of the gate as shown in Figure 20-7. Figure 20-8 shows a sketch of the cross-section of a heater panel embedded into a pier wall. The faceplate serves as both a rub plate and a heat conduction path to uniformly distribute the heat over the area to be protected. The use of rigid conduit for housing the heater elements is consistent with established practice for rub plate heaters used on existing projects. However, in Figure 20-8 the heated area is increased to eliminate, not only the ice in the immediate vicinity of the side seal, but also the entire width of the ice column.

(*b*) A removable cover plate should be provided at the bottom of the conduit to facilitate access to the bottom of the heaters in the rare event that the heaters burn in half and the lower part of the heater needs to be pulled out from the bottom. Consideration needs to be given to whether or not the cover plate at the bottom of the heater conduit will be sealed or not, and if it is not sealed, whether or not it is open to the downstream side (tail water) or upstream side. If the bottom is sealed or open to the tail water, the heater must be designed to operate in air. If the bottom is open to the upstream side, the heater can be specified as an immersion type because the pipe will be filled with water. If the bottom remains open so that water can fill all or part of the pipe, care must be taken to assure that the heaters remain on throughout the winter months and that the temperature in the pipe is maintained above the freezing point to prevent the possibility of water freezing and expanding in the conduit and damaging the conduit, rub plate, or surrounding concrete. This requires continuous monitoring of the heater operation through the winter and the capability to detect a burned out heater and rapidly replace it.

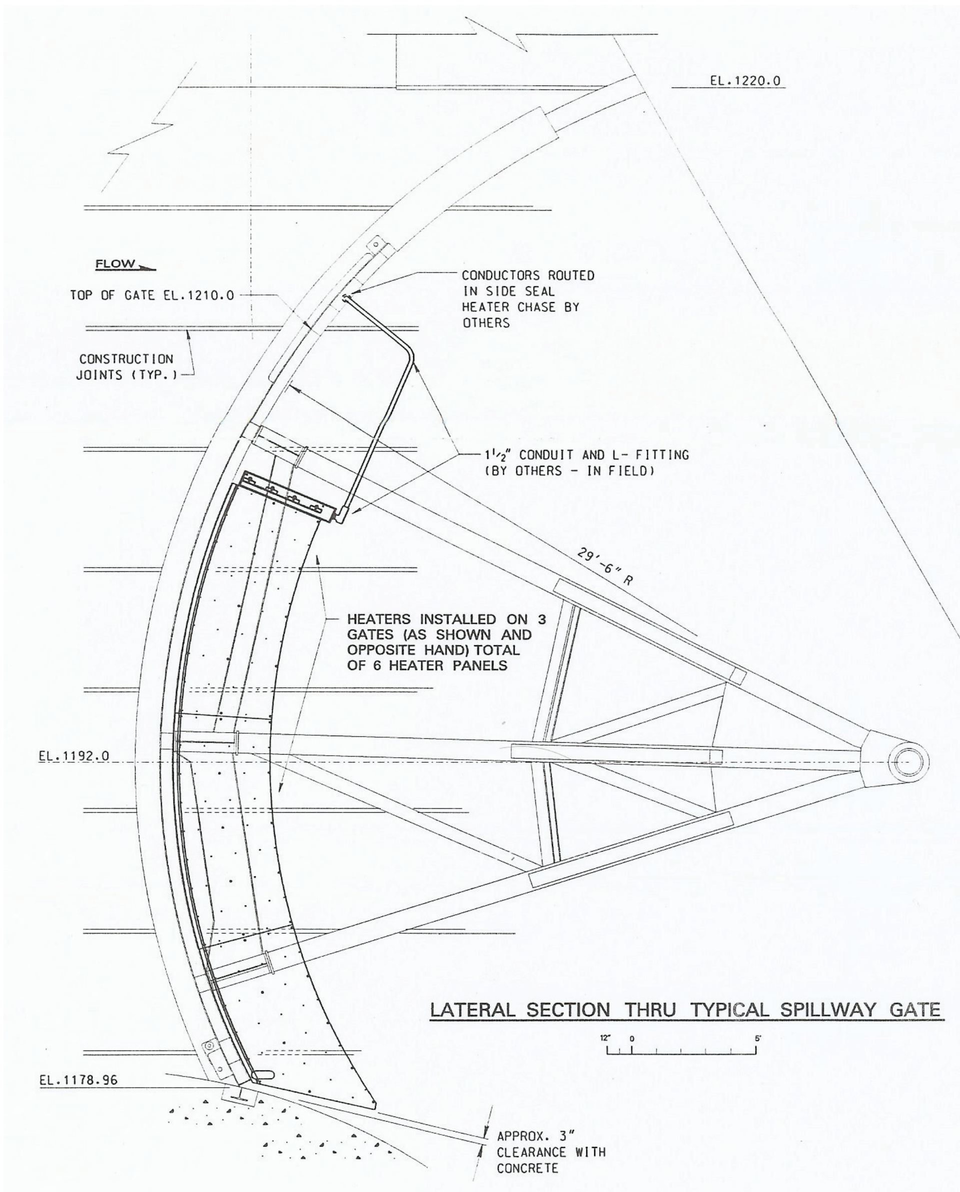


Figure 20-7. Heater panel installed on the pier wall just downstream of the rub plate on the Gavins Point Dam, Yankton, SD (Bockerman and Wagner 1998).

(*c*) No insulation is put in the wall for this application. The thermal conduction of the concrete behind the heaters is quite low and comparable (within an order of magnitude) to typical insulations. In this application, the added benefit of using additional insulation—beyond what the concrete provides—is not offset by the added complexity of inserting insulation into the pier wall.

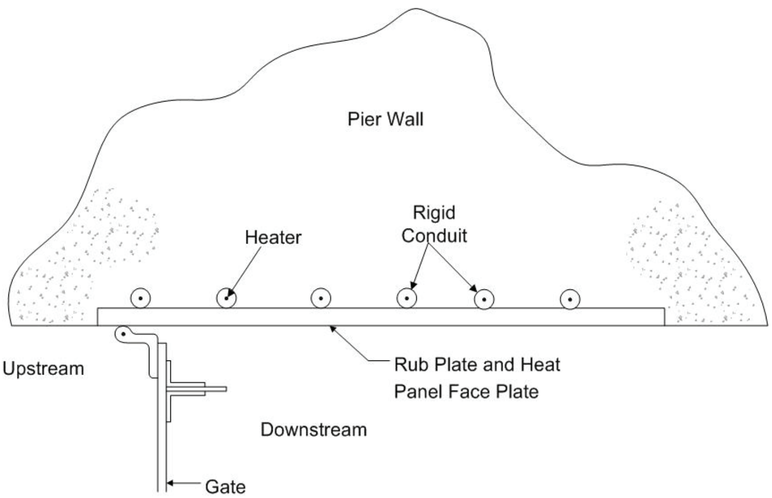


Figure 20-8. Cross-section of a heater panel embedded into a pier wall.

(*d*) For gates that are fully submerged in water, as shown in Figure 20-9, frazil ice can collect and bridge between the upstream side of the skin plate and rub plate. The heater geometry depicted in Figure 20-8 can be used in this case as well, with the exception that the face plate extends upstream of the gate rather than downstream. The length of the heater area generally does not need to be as long in this situation as the frazil does not tend to form columns of ice that extend several feet up the wall; rather, the ice bridge formed by frazil is more local and extending the face plate 0.3 to 0.5 m (12 to 18 in.) upstream of the seal should be adequate.

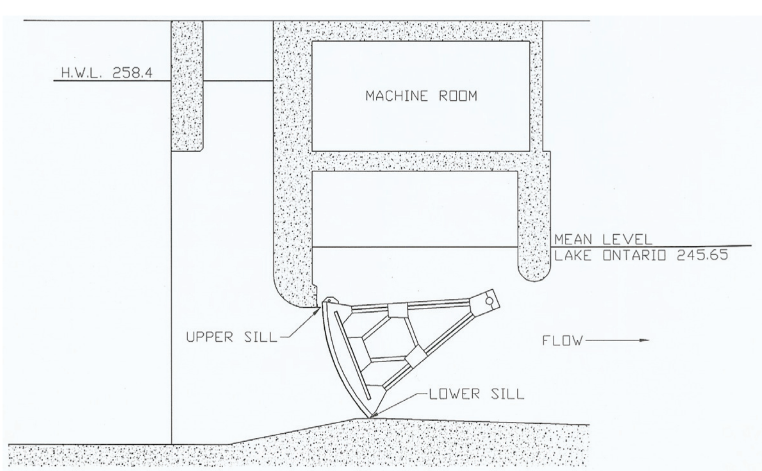


Figure 20-9. Submerged tainter gate (Haehnel and Clark 1998).

(*e*) There are many areas where heating of the concrete wall is desirable, such as lock walls and gate recesses, to shed ice that has accumulated on these walls, thereby inhibiting normal operations. As with rub plate heaters, it is preferred that wall heaters be imbedded in the walls so that they are flush with the surrounding concrete. If it is necessary for heater panels to be surface mounted to the wall, special consideration needs to be given to avoiding the forces of debris, water, ice, barges, etc., that can tear the panel off the wall. The heat required for this application can be determined using the calculations outlined earlier.

(*f*) The recommendation for those areas where embedded electrical wall heaters are needed is a replaceable heater element as described here. During a rehabilitation project, where the concrete walls are to be resurfaced, 1.9-cm-diameter (3/4-in.-diameter) stainless steel pipes can be installed, 15 to 20 cm (6 to 8 in.) on center, with the bottom ends sealed (similar to the geometry shown for rub plate heaters in Figure 20-8). At the top of the pier or along the top of the wall, the top ends of the pipes are accessible so that electrical leads can be run from one vertical pipe to the next. The tubes may be filled with glycol to act as a heat-transfer fluid, once the heater element inserted into the pipe. However, use of glycol is not always permitted by environmental concerns. Alternate techniques of installing the pipes are by drilling vertical holes along the edge of a pier or wall (however, a major concern is the possibility of the hole breaking out) and by cutting vertical slots 7.5 to 10 cm (3 to 4 in.) deep in the wall, and then grouting the pipes into the wall.

(*g*) Consideration should be given to thermally linking the pipes together via a surface mounted plate as shown in Figure 20-8 for rub plate heaters. This will provide more uniform heating of the wall surface and more reliably shed the ice from the wall. Without this, the heater spacing needs to be very small to avoid hot and cold spots on the wall.

(3) *Trunion Arm Heaters*. Ice that bridges between the trunion arm and pier wall can be mitigated with heaters mounted directly on the trunion arm. The location of the heaters should span the length of the trunion arm that may be submerged (either while the gate is opened or closed) during the winter months. A sketch of the construction of such a heater is shown in Figure 20-10. The heaters used for this must be designed to operate both in and out of water (waterproof, non-immersion heaters). The heaters can be either MI cartridge heaters or heat cable. Use of a closed -cell foam insulation as indicated will minimize the heat conduction away from the heated face of the arm and help to reduce the power consumption during heater operation.

(*a*) The heat transfer requirements for these heaters are very similar to other heaters in service on lock and dam walls in the United States as described in Haehnel at al. (2002). Based on this work, heating requirements of 4.5 kW/m^2 are sufficient for submerged applications, which is consistent with the trunion arm heaters described in Haynes et al. (1997).]

(*b*) The heater element can be held in place using suitably sized EMT (electrical mechanical tubing) clamps (or some equivalent clamping device). The cover plate should be removable to allow easy service and replacement of the heater elements.

(*c*) The power supply cable for these heaters can be routed up the trunion arm and pier wall to a common start/stop station. The cable should be housed in rigid conduit along the trunion arm and pier wall; flexible conduit will need to be used to transition from the conduit on the trunion arm to the conduit on the pier wall.

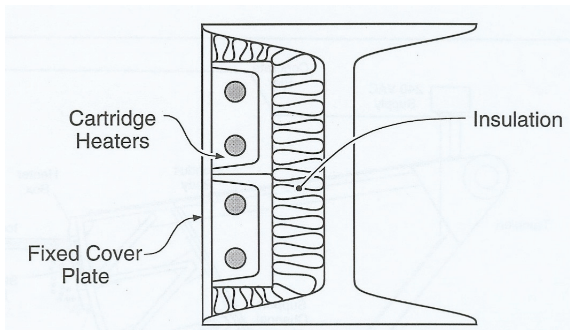


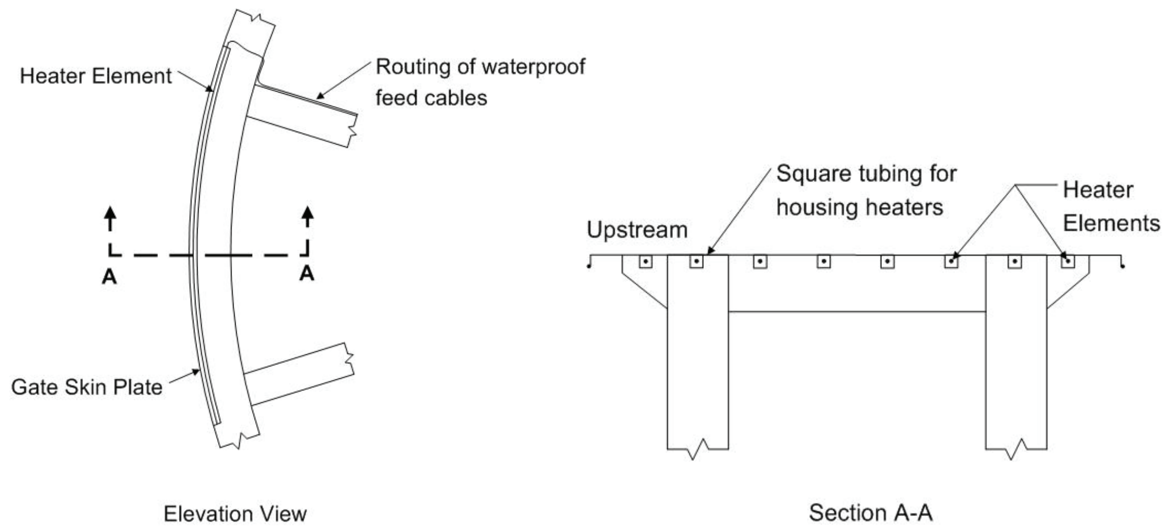
Figure 20-10. Heater construction for a trunion arm. The heater cover plate faces the pier wall (after Haynes et al. 1997).

(4) *Skin Plate Heater.* For a submerged gate, as depicted in Figure 20-9, frazil ice can accumulate on the gate skin plate and cause bridging of ice between the upstream side of the gate and pier walls. This can be eliminated using a skin plate heater system. The heating requirements can be determined using the analysis given in Paragraph 20-2*b*(2)(*b*), and Table 20-3.

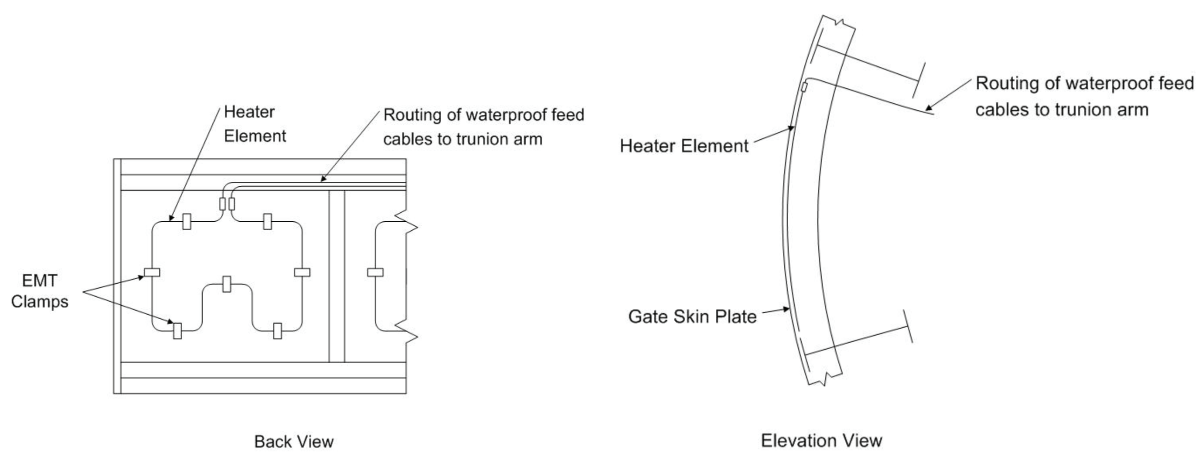
(*a*) Figure 20-11 provides sketches of two possible heater configurations for skin plate heaters. In Figure 20-11a, the heater is shown to follow the arc of the gate skin plate and is housed in square tubing. Mounting the heaters vertically on the gate facilitates easy removal and replacement when the heaters need to be serviced; the heaters are simply withdrawn from the top of the gate. The tubes are not sealed at the bottom; this allows water to come up into the tubing. It is recommended that a removable stop be installed at the bottom of the tubing to prevent the heater from dropping out the bottom of the gate. There should be a gap of 0.8 to 1.3 cm (0.3 to 0.5 in.) between the bottom of the tubing and the stop to allow water to flow into and out of the tubing. The stop will help prevent the bottom of the heater element from being buffeted by turbulent flow and debris as well. This stop can be removed to allow extraction of the heater from the bottom if the heater fails midway and burns in half. Though this rarely happens, it is difficult to extract the lower section of the failed heater if some provision is not made to do so. To facilitate this the bottom of the tubing needs to terminate 8 cm (3 in.) or more from any obstruction (e.g. I-beams or other structural elements) located at the bottom of the gate to give room enough to bend and pull the heater element out the bottom of the tubing.

(*b*) The heater arrangement shown in Figure 20-11b works well when there is a large area free of structural reinforcing on the backside of the skin plate. The heater is held in place with EMT (or similar) clamps and covered with a back plate (not shown) to protect the heater element from debris and water turbulence.

(*c*) The routing of the power supply cable is sketched in Figure 20-11 as well, indicating an approximate routing of the cable, from the face of the gate to the upper trunion arm. From there, the cable would be routed along the pier wall to a start/stop station at the top of the pier. It is anticipated that the cable will be housed in rigid conduit mounted on the trunion arm and pier wall. However, to allow for rotation of the gate about the trunion, a flexible section of conduit will be needed to transition from the trunion arm to the pier wall.



a. Heater elements housed in square tubing bent to follow the arc of the gate.



b. Heater elements attached to the downstream side of the skin plate using EMT clamps.

Figure 20-11. Two skin plate heater designs.

(*d*) Careful consideration needs to be given to the type of heater (immersion or non-immersion) for this application. If the heaters will operate only while the gate is fully submerged (e.g., the geometry shown in Figure 20-9), then immersion type heaters are appropriate. If this is the case, a safety switch should be included in the control circuit to disable the heaters if the gate is brought above water level. In some applications, the heaters may be required to operate while they are only partially submerged. In this case non-immersion, waterproof heaters must be used.

(5) *Intake Trash Racks.* Historically, the most effective method to eliminate ice accumulation on trash racks is to discharge warm water just upstream of the intakes. This keeps the water from being supercooled when it enters the intake, allowing the frazil to pass through the intake without sticking to the bars. The most efficient way to do this is to use waste heat (e.g., discharged cooling water from an industrial or power plant) to heat the water upstream of the gate. Barring the availability of waste heat to prevent icing on the trash rakes, heating the trash rack bars themselves is an effective way for preventing frazil ice buildup. Daly et al. (1992) show that this can be done by placing heaters on the leading edge of the bars, as shown in Figure 20-12. Paragraph 20-2*b*(3) and Table 20-3 can be used to determine the heater size required for this application.

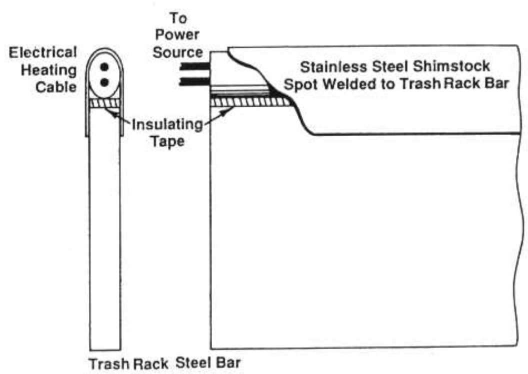


Figure 20-12. Intake trash rack heater system (after Daly et al. 1992).

(*a*) The specified heater diameter needs to be small enough to allow the heater to be slid in and out of the spacing between the shimstock sheathing and the trash rack bar. This allows for replacement of failed heaters without overhauling the trash racks. The shim stock needs to be thick enough to withstand damage from ice, debris, and normal operations. Field tests used sheathing that was 0.25 millimeters (0.01 inch) thick (Daly et al. 1992). Special consideration needs to be given to routing of the cable bundle from the top of each trash rack section to the top of the intake because, for a sizable intake, there may be several hundred individual heaters mounted on the trash rack. One method is to route the cable bundle to the top of the wall through a steel electrical cable raceway recessed into the wall. This raceway may need to be specially designed for this to allow its cover to be removed and the cable installed without having to unscrew the cover from the raceway. One possible approach is to make a cover that slides in a grove over the raceway, such that it can be removed from the top of the intake.

(*b*) Also, special consideration needs to be given to the cables exiting the top of each bar and then being routed back along the top of each trash rack section so that the cables are not exposed to the buffeting of the turbulent flow through the intake, or debris striking the intake. Also, if trash rack rakes (described in Paragraph 20-5*c*) are to be used the cables need to be routed such that they will not interfere with drawing the rakes up the full length of the trash rack assembly.

(*c*) Generally, these would be immersion type heaters. However, in some cases, the top foot or more of the intake may be above the water line. To avoid this condition, it is suggested that in new construction, the elevation of the intake be below the water elevation. If the these heaters are to be applied to an existing intake, it may be necessary to have waterproof, non-immersion heaters at the top of intake, and immersion type heaters in the remaining part of the intake.

(*d*) The total heat requirement to run all of the heaters mounted on a trash rack can be on the order of 1 MW or more. Thus, it is recommended that these be used only when there is a threat of frazil ice blocking the intakes, which is when the water temperature is below freezing. To determine when the water is supercooled requires very precise temperature measurement (to only –0.01°C), so typically the water temperature is not monitored that closely, rather the heaters are thermostatically controlled to come on when the water temperature drops below 0.1°C.

d. Operational Guidance.

(1) *Gate Freeze-up*.

(*a*) It must be noted that the gate heaters are sized for when the gate is closed. Once the gate is opened, the heat loss increases dramatically owing to the high flow through the gate. This may result in the gate freezing in place once opened, because the heaters cannot keep the gate warm enough. Thus, it is recommended that if spillway gates need to be used when the air temperature is below freezing, that they be lifted completely out of the water. Then, once they need to be closed, they be completely closed, so that the heaters can effectively keep the gate ice free.

(*b*) Alternately, the gates may be "exercised" once they are open to prevent substantial ice accumulation from building up and bridging between the gate and pier wall. This requires the gate be moved at least hourly so that hoists can break free the small amount of ice that accumulates while the gates are stationary.

(2) *Intakes*.

(*a*) If the intake is for the power tunnel of a hydroelectric plant, it is important to consider safety regarding operating the turbines when there is a potential for frazil ice in the river. Frazil ice can stick to the trash rack bars and form an ice bridge across the bars reducing or completely stopping the flow through the trash racks. If this were to occur, the differential head across the track rack can be sufficient to cause it to fail. It is advisable that the trash racks be designed to not fail if they become fully blocked leaving, only air inside the power tunnel and water on the other side, so that in the event that they become fully blocked by frazil ice they will not fail and cause damage to the intake, wicket gates, or turbine.

(*b*) It is also advised that the differential pressure head across the trash racks be measured at all times. Provided they are not blocked, the differential head will be zero. As the trash racks become blocked by frazil, the differential head will increase, indicating that a problem is developing and that action needs to be taken to prevent further ice accumulation.

(3) *Heater Controls.* In the control circuit, timers and thermostats can be added to limit power consumption. It is recommended that the heaters be thermostatically controlled to minimize power usage, which requires the temperature sensors (e.g., RTD type) be located on or near the heaters and controllers that will accommodate temperature feedback control.

(*a*) For gate and wall heaters, the temperature sensors are typically located between heater elements and mounted on the surface to be protected by the heaters. These sensors need to be located about midway along the length of a heater element so that the measurement is representative of the general temperature distribution on the surface to be protected. These also should be housed in a conduit to allow replacement when they fail. For the trash rack heaters the temperature sensor should be located in the water with the cable in protective conduit and the sensor head protruding into the flow.

(*b*) Surface mounted RTD sensors should be used for the skin plate and trunion arm heaters. These may conveniently be held in place with a threaded fastener. For the rub plate heaters, a cartridge style RTD may be more suitable. This can be slid into a conduit embedded in the wall.

(*c*) For intake trash rack heaters, a cartridge type RTD sensor may be used. It can be housed in a rigid conduit that extends down into the water flow. The conduit serves to protect the sensor and cable from debris damage. The tip of the RTD sensor can protrude out the end of the conduit into the water and is held in place with a water-tight cable clamp. It is recommended that water not be allowed to get into the conduit as it may rupture the conduit when it freezes. The conduit housing the RTD sensor can be fastened to the concrete wall that is adjacent to the intakes.

(*d*) It is not always necessary to run heaters continuously. Often the needed benefit can be achieved by cycling though the heater banks at regular intervals to shed the ice that has accumulate in the intervening time. This requires breaking the heater system into logical subsections that can be controlled through a timing circuit. Set up in this manner, the entire heater system not only requires less power, but also less energy, while still providing the desired protection.

(4) *General Guidance*. Some heater manufacturers recommend that electrical heaters remain on year round when they are in air to prevent excessive moisture from building up on the heaters and causing oxidation and corrosion. Using thermostatic control, the power required during the summer months to keep the heaters dry will be substantially reduced. If the heaters are cycled off, the manufacturer recommends that they be brought back on line in stages, rather than bringing them up to their rated output all at once.

(*a*) As the cold leads for the heater elements are all terminated in a start/stop station enclosure (located in a machine room), the condition of the heaters can be readily evaluated from top side by checking the electrical resistance of the heaters using an ohmmeter, to detect an open circuit, or current meter, to determine if the heater performance has degraded. In the former case, the heater has completely burned out and the circuit is open, which can be detected with an ohmmeter. More often heater performance degrades over time, which can be monitored by measuring the current drawn by the heater. At the rated current, the heater puts out the rated heat capacity. As the current draw of a heater decreases, so too does the heater output, and the heater system will no longer be able to keep the surface it is protecting ice free. Because the current draw of a heater element is directly proportional to the heat given off, one can estimate the reduction in heater performance by

$$Q_{\text{actual}} = Q_{\text{rated}} \frac{A_{\text{measured}}}{A_{\text{rated}}} \tag{20-22}$$

where

A_{measured} = measured current draw of heater
A_{rated} = rated current of the heater
Q_{rated} = Rated heat output of the electrical heater element (W)
Q_{actual} = Actual output of the heater element (W).

If the heater capacity is over-designed by a factor of S, then the element needs to be replaced when

$$\frac{A_{\text{measured}}}{A_{\text{rated}}} \leq \frac{1}{S}\,. \tag{20-23}$$

where S = factor of safety for heater system.

(*b*) The cold leads for electrical heaters must be clearly marked as to which heater it is connected. This will allow identification of which type of heater needs replacement, and where it is located, simplifying the replacement process. This is particularly important when the heaters need to be replaced by divers, enabling the divers to know exactly which heaters need to be replaced and where they are located before they begin their dive.

(*c*) Other methods of providing heat to a surface are acceptable, such as pumping a heated fluid through pipes embedded in a wall or on the surface of a gate. The heat requirements for such systems can be determined using the guidance provided in Paragraph 20-2*b*. Some concerns related to the use of fluid based systems include:

- Use of toxic substances, such as ethylene-glycol, that can leak into the environment.
- Use of water that can freeze and burst the pipes in the wall if the pump system fails.
- Corrosion of the pipes.

If fluid based systems are to be used, these concerns need to be addressed.

20-3. Controlling Water Leakage by Seals.

a. Heated J-seals on Dam Gates. Heating the side J-seals improves their ability to reduce leakage past tainter gates, and thus reduce the associated buildup of icing on the walls and the gate structures. This method is easily adaptable at low cost to existing dam gates (using Huntington J-seal Mold No. 3493 or equivalent).

(1) This in situ heating system has been made up so that it can be inserted into the hollow channel of a J-seal; it keeps ice from forming on the seal and increases the flexibility of the seal at lower temperatures. With increased flexibility, the seal better conforms to irregular surfaces, thereby reducing leakage to the downstream side. With little or no leakage, ice formation on the cold, exposed downstream side is substantially reduced. Neither steaming nor "cindering" (i.e., pouring cinders in the water above the locations of the greatest leakages, so that the cinders flow toward the leaks and plug them) were required during tests of the in situ heating system at Starved Rock Lock and Dam on the Illinois Waterway, where it was installed during a dam rehabilitation.

(2) The self-regulating heat trace tape, 208 V ac at 121 W/m at 0°C (37 W/ft at 32°F), was cut from a spool to a length of 5.5 m (18 ft). The heat tape was sealed at one end. The other end had a cold electrical lead attached to connect to the electrical power. The J-seal and the inserted heater are shown in Figure 20-13. The 1988 cost of Huntington J-seal Mold No. 3493 was $45.57/m ($14.50/ft). The seal was manufactured as of 1988 by Buckhorn Rubber, 55 W. Techne Center Drive, Milford, Ohio 45150 (800-543-5454). The self-regulating heat trace tape is widely available at an approximate 1988 cost of $16.40/m ($5/ft). If both seals of a gate are heated and the heaters are operating at maximum power, the operating cost per day is $2.24, assuming 1332 W at $0.07/ kWhr.

(3) Use of heated J-seals would not preclude the inclusion of embedded electrical heaters in gate pier walls in rehabilitations or new designs, because embedded heaters aid in keeping seal plates ice-free above or below the immediate seal-contact area, so that gates can easily be placed in any chosen position.

b. Side Seal Heaters, Seal Design, Cinders. The performance of the J-bulb seal can also be improved by increasing pre-load and providing a softer seal. Also, the seal depends on hydraulic head to work properly, that is why seal tend to leak near the top of the gate where the head is small, and seal better further down. Factors that will impact the extent of leakage are

- Proper seal installation.
- Surface corrosion of the mating rub plate surface.
- Seal damage.
- Seal wear.
- Silt and debris caught between seal and mating surface.
- Stiffening of the seal due to aging.
- Unevenly resurfaced mating surface.

(1) All of these factors make it difficult to have zero leakage in any seal design. An incremental improvement in sealing may be achieved by resurface the mating surface with stainless steel.

(2) As mentioned above it is common practice at many projects to use cinders to prevent leakage by the side seal on tainter gates. This is done by dropping handfuls of cinders from the surface into the water over where a seal is leaking. By trial and with experience, the leak can be plugged. The this is often done in the fall and prevents ice accumulation along the side seal through the winter provided the gate remains closed. However, once the gate is moved, the seal is broken, the cinders are lost, and the procedure needs to be re-done to seal the gate again. Thus, for gates that need to be regularly moved throughout the winter months, this may not be a viable solution.

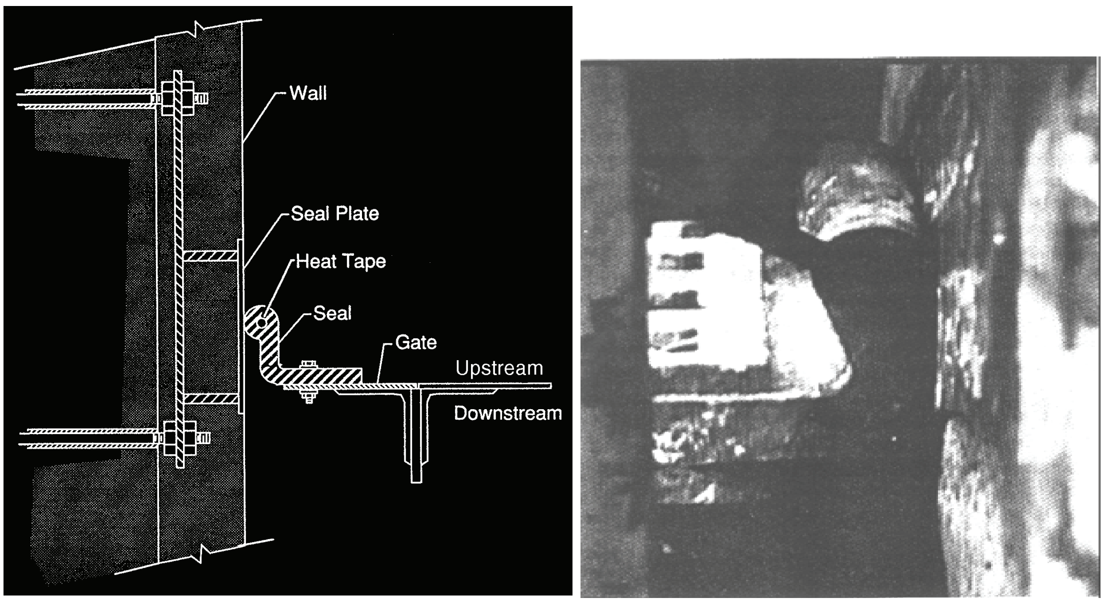


Figure 20-13. J-seal and J-seal heater installation on a tainter gate.

20-4. Surface Treatments to Reduce Ice Adhesion.

a. Materials. There is a long history of study in this area for a variety of applications, but surface treatments that shed ice reliably and repeatedly have not yet emerged. The only chemical treatment that has been used successfully on a large scale for truly shedding ice is repeated application of chemicals that depress the freezing point of water. As far as concrete surfaces are concerned, the classic treatment for ice removal is repeated application of sodium chloride or calcium chloride. Use of these on hydraulic structures is almost universally not acceptable because of environmental concerns. Another ice-control method is a permanent or semi-permanent coating that reduces the adhesive force between the coated surface and the ice that forms on it. The ideal material would be one that prevented ice formation entirely. No known coatings do this, but some make the task of ice removal from coated surfaces easier. While many available coatings and claddings reduce the ice bond strength significantly, they are not enough to eliminate the need for additional methods of ice removal. To have the ice shed off a vertical surface under its own weight, the adhesion strength must be less than the shear stress that the ice exerts on the wall. For example, the adhesion strength of the ice to the substrate would have to be less than 5 kPa for a 0.6-m-wide ice collar to fall off a vertical surface under its own weight. This requires about a factor-of-8 reduction in ice adhesion strength in comparison to the best available coatings and materials. Consequently, low-energy materials should be considered system enhancements for other methods, such as heat, steam lances, and pike poles. Note that care must be exercised when using mechanical methods to remove ice from a coated surface since the coatings can be abraded or chipped off by pike poles, etc.

(1) Numerous materials, coatings, and paints are commercially available that are advertised to have low-friction or non-stick properties. Some of these coatings are also marketed as ice-phobic (i.e., significantly lowering the adhesion strength of ice). The ice adhesion strength for many of these coatings and materials have been measured in the laboratory to rank their relative performance (e.g., Haehnel and Mulherin 1998). Included in this is measured the ice adhesion strength of common paints used by the Corps of Engineers to protect steel members on hydraulic structures. Both vinyl-based paints (used at freshwater projects) and epoxy paints (used mainly for salt/brackish water applications) were evaluated. Because the paints used by the Corps have been primarily developed for their high durability, it was considered unlikely that the low-adhesion coatings would replace them, but instead would be applied over the Corps paints to reduce ice adhesion to the surface. Consequently, some of the laboratory tests were designed to simulate this condition, and ice-phobic coatings were layered over samples already having the Corps paints applied.

(2) An alternate means of protection might be to clad an area with a low-adhesion material. Consequently the ice adhesion strength for several candidate plastic cladding materials, such as Teflon™, acetal, and polyurethane, have also been measured. Table 20-4 lists the paints, low-adhesion coatings, and materials evaluated. These tests were all conducted at –10°C.

(3) Comparisons of the adhesion strengths of these different coatings and claddings are shown in Figure 20-14. The best performing material in all of these coatings and claddings is R-2180, which drops the adhesion strength by a factor of 40 over bare steel and aluminum surfaces, and is approximately 10 times better than any other coating on the market.

(4) Figure 20-14 presents results for tests conducted on pristine samples. However, to study the effect of weathering on ice adhesion, the pristine plastic and coated carbon steel samples were mounted in a navigation lock chamber on the Mississippi River near St. Louis, MO (Lock and Dam 25), and exposed to field conditions, including cyclical wetting and drying and abrasion from moving ice, sediment, and debris, for the duration of the 2001–2002 winter and spring seasons. Not all of the materials presented in Figure 20-14 and Table 20-4 were subjected to these weathering tests because they were not available at the time.

Table 20-4
Materials and coatings evaluated at CRREL to measure the adhesive shear strength of ice (after Haehnel et al. 2002)

Material	Composition
	Paints and coatings
Kiss-Cote 1083	Kiss-Cote 1083 (polydimethyl siloxane) used on aluminum samples. KISS-COTE, Inc. 12515 Sugar Pine Way Tampa, FL 33624 Phone: (813) 962-2703 http://www.kiss-cote.com/
Kiss-Cote ML	Kiss-Cote MegaGuard LiquiCote (polydimethyl siloxane) used on aluminum samples and painted steel samples. KISS-COTE, Inc. 12515 Sugar Pine Way Tampa, FL 33624 Phone: (813) 962-2703 http://www.kiss-cote.com/
BMS 10-60	BMS (Boeing Material Spec) 10-60 polyurethane over BMS 10-11 epoxy primer. http://www.boeing.com/companyoffices/doingbiz/environmental/high_solids.html
Wearlon	Wearlon Super F1 (water-based, methyl silicone copolymer epoxy). Environmental Coatings P.O. Box 405 Maryville, IL 62062 Phone: 888-Wearcon www.environmentalcoatings.com
PSX-700	Siloxane and polyurethane epoxy. Ameron International Protective Coatings Group 201 North Berry Street Brea, CA 92821 Phone: (714) 529-1951 http://www.psx700.com/
Interlux Brightside	Polyurathane alkyd. International Paint Inc. 2270 Morris Ave Union NJ 07083 Phone: (908) 686-1300 http://www.yachtpaint.com/usa/

Material	Composition
TroyGuard	Fluoropolymer suspension and mineral spirits in clear acrylic urethane paint. The additive is produced by: Troy Corporation 8 Vreeland Road Florham Park, NJ 07932-0955 Phone: (973) 443-4200 http: www.troycorp.com Tested coating with Troyguard EX527 additive was produced by: Niles Chemical Paint Company, 225 Fort Niles, MI 49120 Phone: (616) 683-3377
TroyGuard/ polyurethane	Fluoropolymer suspension and mineral spirits in BMS 10-60 polyurethane paint The additive is produced by: Troy Corporation 8 Vreeland Road Florham Park, NJ 07932-0955 Phone: (973) 443-4200 http: www.troycorp.com
Inertia 160	Trimethyl hexamethylenediamine epoxy. International Paint Inc. 6001 Antoine Dr Houston TX 77091 Phone: (713) 684-1254 http://www.international-marine.com/
Envelon	Resin-based ethylene acrylic acid copolymer thermoplastic. Thermoset Applications Group Dow Plastics The Dow Chemical Co. 2040 Willard H. Dow Center Midland, MI 48674 Phone: (800) 441-4369 http://www.dow.com/plastics/
Slip Plate #1	Natural graphite coating in mineral spirits. Superior Graphite Co. 10 South Riverside Plaza-Suite 1600 Chicago, IL 60606 Phone: (312) 559-2999 http://www.graphitesgc.com/

Material	Composition
WC-1-ICE	Saturated polyester resins in fluoropolyol with PTFE and organofunctional silicone fluid additives, modified with a fluorotelomer intermediate, and activated with a trimer of HDI. 21st Century Coatings, Inc. 4701 Willard Ave., Suite 109 Chevy Chase, MD 20815 Phone: (301) 657-6230 http:www.fpu-coatings.com
SA-RIP-4004	Saturated polyester resins modified with fluorotelomer intermediates activated with a biuret of HDI. S&A Fernandina, Inc. 3601 Crow Court Jacksonville, FL 32259 Phone: (904) 230-1799
51PC951	A fluorinated polyurethane coating, suitable for both in-air and in-water immersion, produced and sold by 21st Century Coatings (Canada) LLC
R-2180	A two-part silicone elastomer dispersed in xylene, produced and sold by NuSil Technology, LLC (http://www.nusil.com/PDF/PP/R-2180P.pdf).
Corps Paints	
V-103c	Vinyl resin, type 3 (20), carbon black (1.5), diisodecyl phthalate (3.4), methyl isobutyl ketone (36.0), toluene (39.1% by weight). Indmar Coatings Corporation 237 West Main St Wakefield VA 23888 Phone: (757) 899-3807
V-766e	Vinyl resin, type 3 (5.6) and type 4(11.6), titanium dioxide and carbon black (13.0), diisodecyl phthalate (2.9), methyl isobutyl ketone (32.0), toluene (34.7) ortho phosphoric acid (0.2 % by weight). Indmar Coatings Corporation 237 West Main St Wakefield VA 23888 Phone: (757) 899-3807
V-102e	Vinyl resin, type 3 (18.2), aluminum powder (8.3) diisodecyl phthalate (3.1) methyl isobutyl ketone (33.8), toluene (36.6 % by weight). Indmar Coatings Corporation 237 West Main St Wakefield VA 23888 Phone: (757) 899-3807

Material	Composition
C-200a	A coal tar epoxy formulation commonly used on U.S. Army Corps of Engineers hydraulic structures exposed to brackish or salt waters. Tested coating was “Bitumastic 300M”, and was produced by: Carboline Company 350 Hanley Industrial Court St Louis MO 63144 Phone: (314) 644-1000
MIL-P-24441C Type III	A polyamide epoxy formulation commonly used on U.S. Army Corps of Engineers hydraulic structures where VOC-compliance is mandatory. Tested coating was produced by: Indmar Coatings Corporation 237 West Main St. Wakefield VA 23888 Phone: (757) 899-3807
Materials	
Teflon™	Polytetrafluoroethylene (PTFE) thermoplastic
Polyethylene	Ultra-high-molecular-weight polyethylene thermoplastic
Acetal	Acetal copolymer thermoplastic
Titanium	ASTM B348 - Grade 5 (6% aluminum, 4% vanadium)
Dupont Delrin™	Polyoxymethylene homopolymer thermoplastic
Carbon Steel	Cold-rolled 1018
Stainless Steel	Type 410
Aluminum	Type 7075

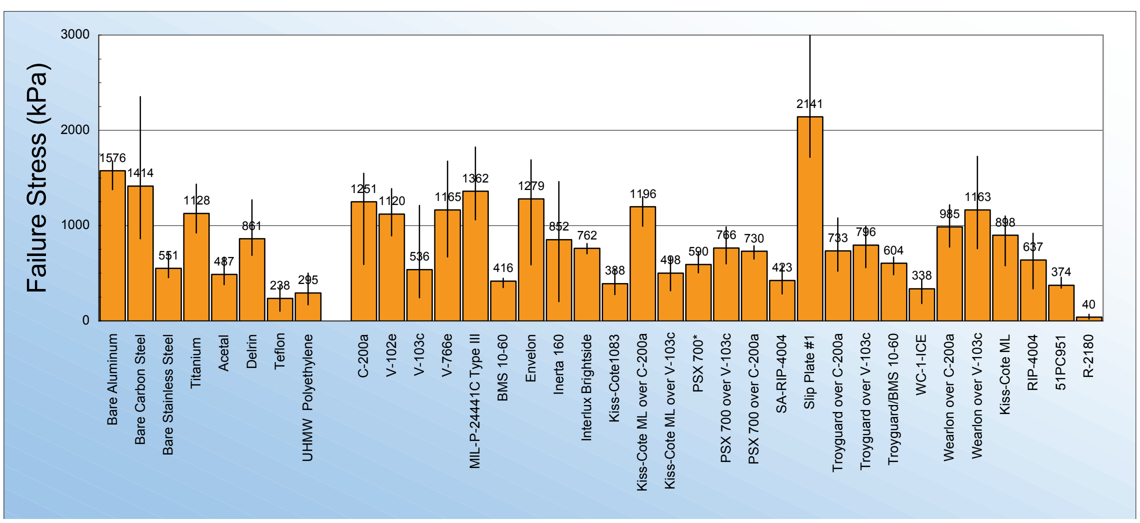


Figure 20-14 Ice adhesion test results for construction materials and commercial coatings. Column heights represent average ice adhesion strength, which is also given as a numerical value on the top of each column. Error bars represent the range in the data.

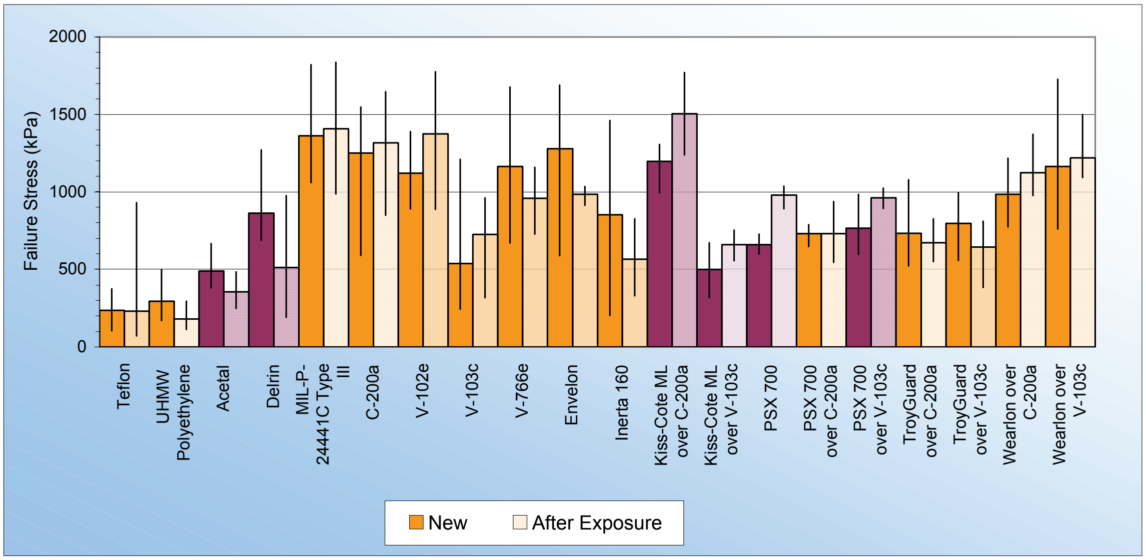


Figure 20-15. Ice adhesion test results for potential low-adhesion coatings and materials. Samples were tested before and after being placed below water level in a Mississippi River navigation lock for a 4-month-long summer season where they were subjected to repeated draining and flooding associated with normal lock operations. Column heights represent average adhesion values. Error bars represent the range in the data. Orange columns indicate material that have no statistically significant difference between before- and after-exposure test values. Purple data were significantly different at the 95% confidence level.

(4) The results of this evaluation are presented in Figure 20-15. Most of the materials did not exhibit a statistically significant change in their ice adhesion performance during these weathering tests; these materials are indicated in Orange in Figure 20-14. Yet, six coatings or claddings did demonstrate a significant change in their performance attributable to weathering. All of the coatings exhibited an increase in adhesion strength from weathering, while the claddings showed a decrease in adhesion strength. This indicates that some of the claddings may perform better with time, while for some of the coatings their performance will degrade over time.

(5) All of the tests conducted to date have shown that the adhesive shear strength of ice bonded to a variety of materials and coatings varies by a little more than an order of magnitude. For the pristine plastic samples, the variation in adhesion strength between Teflon™ (lowest bond strength) to Delrin™ (highest bond strength) is less than a factor of four. Similarly, the bond strength of ice to carbon steel painted with V-103c is approximately three times lower than that of bare carbon steel. The most significant reduction in ice strength is that exhibited by R-2180 coated over aluminum; the reduction in ice strength of this coating, in comparison to bare aluminum is almost a factor of 40.

b. *Copolymer Coatings.* Although this material was not evaluated with the other coatings previously mentioned, it has been successfully used in the field. One successful material is a long-chain copolymer compound made up of polycarbonates and polysiloxanes. The most effective coating of the many that have been tested is a solution of polycarbonate–polysiloxane compound, silicone oil, and toluene. The mixture is highly volatile and leaves a thin coat of the copolymer and silicone on the surface to which it is applied.

(1) The copolymer coating should not be applied to a concrete surface unless it is certain that the concrete behind the coating can resist frost action in a critically saturated condition. Proper application guidance for surface coatings to concrete can be found in *Maintenance and Repair of Concrete and Concrete Structures,* EM 1110-2-2002. The surface to be coated must be clean and dry. For concrete and metal surfaces (bare and painted), steam cleaning is sufficient; however, a detergent may be added to the water of the steam cleaner. This was done, for example, in one case where navigation lock walls were heavily coated with oil and algae. Once the surface is clean and dry, the solution can be sprayed on using an airless spray gun system (Figure 20-16). A single pass will deposit a coat 25 to 51 μm (1 to 2 mils) thick. Three coats are recommended for a coating thickness of about 127 μm (5 mils). Achieving this final thickness requires about 24.4 L/100 m^2 (6 gal./1000 ft^2).

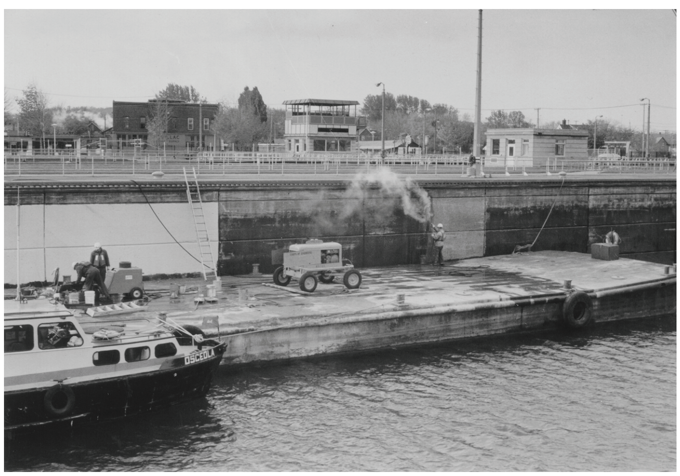


Figure 20-16. Airless spray gun system in use.

(2) Care has to be taken when mixing the solution. Toluene is a combustible material, so no electrical motor-driven mixer should be used. An air-operated drill motor fitted with a rod with mixer blades has worked satisfactorily. The fumes may also be a health hazard, so that a well-ventilated mixing area should be used. A 208-L (55-gal.) drum fitted with a bracket to hold the drill motor is a suitable mixing container. Batches of up to 151 L (40 gal.) can easily be handled. The liquid portions, toluene and silicone oil, are placed in the container first. Then the mixer is started and the copolymer powder is slowly added. Mixing continues until all solids are dissolved. Then the solution can be transferred to a storage container.

(3) Tests to determine the merits of an undercoating for the copolymer (on concrete surfaces that are worn and rough) show that an epoxy-type coating that acts as a filler over the

rough concrete provides a better surface to which the copolymer adheres. Trials of the undercoating and copolymer were done at the Poe Lock, at the St. Marys Falls Canal, at Sault Ste. Marie, Michigan, at Lock No. 4 on the Allegheny River, and at the Starved Rock Lock on the Illinois Waterway. Maintenance and frequency of recoating requirements were monitored. The coating remained in good condition for at least 3 years.

c. Epoxy Coatings. Commercially available two-part epoxy coatings are durable and give concrete ideal protection against the ingress of chloride ions, carbon monoxide, and other corrosive agents over the design life. The hard, smooth finish provides a very low friction coefficient, thus reducing the bond strength between ice and substrate.

d. Claddings. In a demonstration at Starved Rock Lock in Illinois, a 1.2- × 2.4-m × 1.2-cm-thick (4- × 8-ft × ½-in.-thick) sheet of high-density polyethylene was fastened to the curved part of the gate recess wall at the quoin end, at the ice-collar level. Hilti studs, 0.5 m (20 in.) on center, were used for attaching the sheets. Ice formed on the polyethylene surface and the concrete surface equally, but far less effort was needed by lock personnel to manually remove the ice from the plastic material, because of the lower adhesion forces between the polyethylene and the ice. Problems were noted with ice being more difficult to dislodge where the studs protruded, but a redesigned fastening technique could overcome that problem. The polyethylene is not highly durable when pike poles or ice chippers have to be used extensively, though. The use of steam to dislodge the ice collars would eliminate the risk of this damage. The panels are easily and economically replaced, since their 1988 cost was only about $75/m^2 ($7/ft^2).

20-5. Mechanical Removal of Ice. A number of mechanical methods have been used with varying degrees of success to remove ice from lock walls, dam gates, intakes and other critical locations. Some of the mechanical methods used are described below.

a. Mechanical Contact Tools for Ice Removal. Two hand tools that can reliably be used to remove ice from concrete or steel surfaces are the pike pole and the ice chipper. Both of these tools are widely used by lock personnel at sites that experience winter icing problems. Figure 20-17 is a sketch of an ice chipper that has been refined over many years by its users. Large mechanical equipment used to scrape ice collars from lock walls have been used on a limited basis. Backhoes scrape the wall vertically by drawing the bucket teeth up the face of the concrete. With a light machine, this may require more than one pass to scrape through to the concrete, and frequent repositioning of the machine is necessary. With a heavier track-mounted machine, a single pass is usually sufficient. It is easy to move the machine along and there are no spuds to be set. However, with forceful operation, damage to the lock wall is inevitable, and the concrete on grooved or paneled walls could be seriously spalled.

b. Ice Removal with Non-contact Tools. Two techniques for ice removal using non-contacting tools are steam and water jets. Steam, when available at the desired locations, has always been used, often via lances or pipe probes placed and maneuvered by hand. But using steam is slow and time-consuming. The use of high-pressure water jets is rare because of the high horsepower required and the bulkiness of the typical systems. Advances in the design of such systems could make them more attractive.

c. Ice Control at Intakes. One solution for controlling frazil ice accumulation on intakes is to manually clean the trash racks during the periods when frazil ice is in the river, using special built trash rack rakes. These rakes have long handles that allow drawing the rake up across the full length of the trash rack and the tines on the rake are spaced so they fit between each of the bars on the trash rack. If this method is to be employed, it is recommended that a deck with railings be installed above the intakes that extends out over the wall. Also, there needs to be a slot in the deck to allow the rake to pass between the wall and deck to access the front of the trash racks. This deck will allow personnel to reach out over the wall while they are pulling the rake up without putting them at risk of falling in the water. As it is so frequent that frazil ice problems occur at night, provision will need to be made to bring on a crew at short notice to rake the trash racks. The crew will likely need to work all night long. To accommodate this, a warming shelter near the intakes should be installed to give a place for personnel to rest and get out of the weather during breaks.

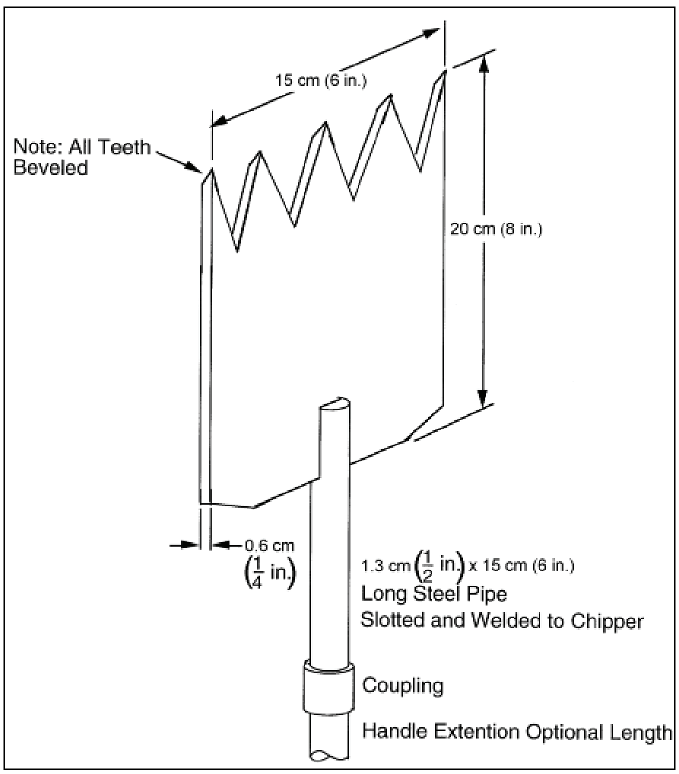


Figure 20-17. Effective design for a manual ice-chipping tool.

20-6. References

a. Required Publications.

None.

b. Related Publications.

(1) *Army Publications*.

EM 1110-2-2002
Maintenance and Repair of Concrete and Concrete Structures

(2) *Other Publications*.

Billfalk (1987)
Billfalk, L. (1987) *Ice Problems in Hydro Power Plants*. Report U(L) 1987/15, Vattenfall Alvkarlebylboratoriet, Alvarkarleby, Sweden.

Bockerman and Wagner (1998)
Bockerman, R. W., and P. A. Wagner (1998) Solutions to Gavins Point tainter gate icing problems. In *Proceedings of the Engineering Technology Transfer & Training Conference, Kansas City, MO, 2–4 June*.

Daly et al. (1992)
Daly, S. F., Haynes, F. D., Garfield, D. E., and Clark, C. H. (1992) Field tests of a surface-heated trash rack to prevent frazil ice blockage. In *Proceedings, 11th International Symposium on Ice, IAHR, 15–19 June, Banff, Alberta, Canada*. Vol. 1, p. 71–78.

Haehnel et al. (2002)
Haehnel, R., Mulherin, N., and Tuthill, A. (2002) Advances in icing control at navigation and hydroelectric structures. In *Proceedings of 11th International ASCE Conference on Cold Regions Engineering, Anchorage, AK, 20–22 May*, p. 748–760.

Haehnel and Mulherin (1998)
Haehnel, R.B. and Mulherin, N.D. (1998) The bond strength of an ice–solid interface loaded in shear. In *Ice in Surface Waters, Proceedings IAHR 14th International Symposium on Ice, Potsdam, NY, 27–31 July*, p. 597–604.

Haehnel and Clark (1998)
Haehnel, R. B., and Clark, C. H. (1998) Maintaining operation of bypass tainter gates during frazil ice conditions at the Heywood Generating Station. Contract Report prepared for St. Catharines Hydroelectric Commission, St. Catharines, Ontario. Hanover, NH: U.S. Army Cold Regions Research and Engineering Laboratory.

Haynes et al. (1997)
Haynes, D., Haehnel, R., Clark, C., and Zabilansky, L. (1997) Ice control techniques for Corps projects. REMR-HY-14. Vicksburg, MS: Waterways Experiment Station.

Logan (1974)
Logan, T. H. (1974) Prevention of frazil ice clogging of water intakes by application of heat, REC-ERC-74-15, U.S. Department of Interior, Bureau of Reclamation, Engineering and Research Center, Denver, CO.

Reid (1928)
Reid, C. R. (1928) Electric heating of rack-bars in hydroelectric plants. *The Engineering Journal*, April, p. 263–265.

Ruths (1924)
Ruths, A. (1924) Ice troubles in Norwegian power plants. In *Transactions, First World Power Conference, London*, p. 771–787.

Samsioe (1924)
Samsioe, A.F. (1924) Measures taken in Sweden against ice troubles at water power plants. In *Transactions, First World Power Conference, London*, p. 806–811.